ROSAT Observations of the Primary and Secondary Streams of Interstellar Neutral Atoms

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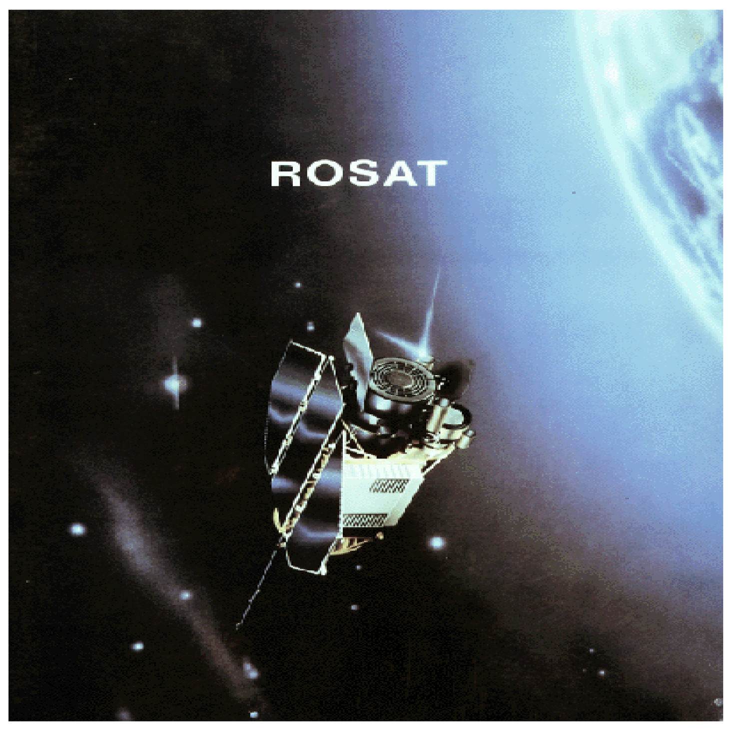

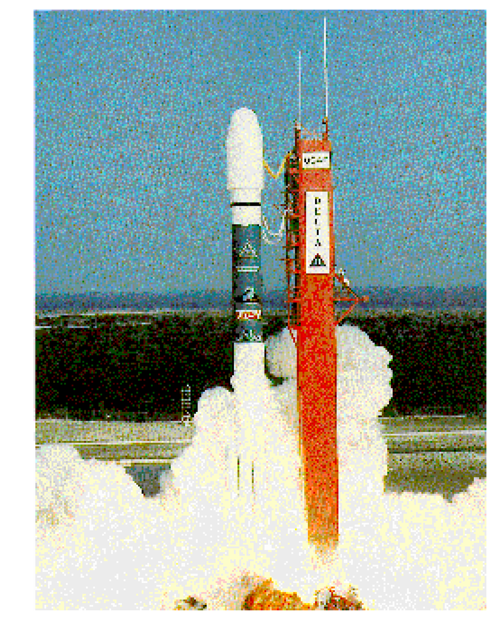

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1. Introduction

Initial analysis of ROSAT All-Sky Survey data suggests:

- **A value of α consistent with 6x10^{-16}eV cm^2.**
- **A heliospheric contribution to the total X-ray flux ranging from 18% five to ten degrees off-axis to about 40% on-axis viewing southward.**
- **A secondary stream entering from above the ecliptic which may contain 3-4 times the neutral density of the primary stream at 1 AU.**

The downstream focusing cones for both the primary and secondary streams of interstellar neutral atoms are observed in the ROSAT All-Sky Survey data.

Heavy neutral atoms entering the heliosphere from the interstellar wind are focused downstream of the Sun into a focusing cone, creating a region of enhanced neutral density. Solar wind high charge state ions charge exchange with these neutrals and, in the process, emit soft X-rays (~0.25 keV). In this presentation, we discuss ROSAT X-ray observations of both the primary and secondary streams of interstellar neutral atoms [Collier et al., Adv. Space Res., in press, 2003]. Results of the analysis indicate a value of α consistent with about 6x10^{-16} eV cm^2 (e.g. Cravens, T.E., Ap. J., 532:L153, 2000, eq. 2), a heliospheric contribution to the total X-ray flux ranging from about 18% at about five-ten degrees off the downstream axis to about 40% directly above the downstream axis viewing southward, and a secondary stream entering the heliosphere from above the ecliptic plane which may contain 3-4 times more neutral density at 1 AU than the primary stream, at least during the time of the ROSAT All-Sky Survey. The origin, properties and implications of this secondary stream need to be examined before we can have any confidence that our understanding of the heliosphere is not flawed.

In this presentation, we concentrate on ROSAT downstream observations only. This means helium in the case of the primary stream and heavies, maybe helium as well, for the secondary stream.

2. X-rays from Comets

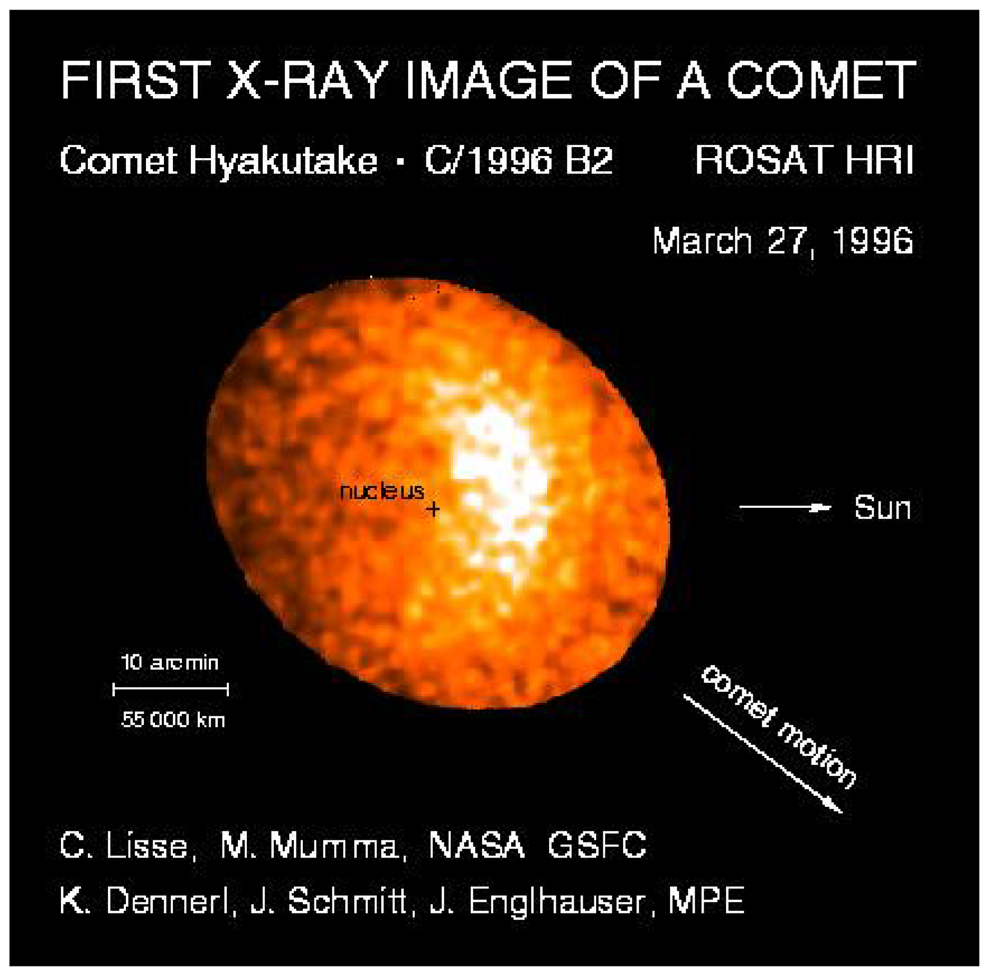

Figure 1. The first observation of X-ray emission from a comet, observed by ROSAT.

In 1996, the Rontgen X-ray Satellite (ROSAT) observed X-ray emission from comet Hyakutake [Lisse et al., Science, 274, 11 Oct 96], as shown in Figure 1. This was a mystery at the time as it was unknown why comets would emit X-rays.

It was eventually determined that cometary X-rays result from high charge state solar wind ions (e.g. O^{+7} and O^{+6}) charge exchanging with cometary neutrals and ending up in an excited state. When the excited state relaxes, X-rays are emitted.

Cravens et al. [JGR, 106, 24,883, 2001] took this one step further and argued that if X-rays resulted from solar wind charge exchange with cometary neutrals, then they should result from solar wind charge exchange with interstellar and exospheric (i.e. terrestrial) neutrals, as well.

Figure 2 shows a figure from Cravens et al. [JGR, 106, 24,883, 2001] showing that the solar wind flux correlates extremely well, at the 0.7 level, with the 0.25 keV LTE X-ray data on ROSAT.

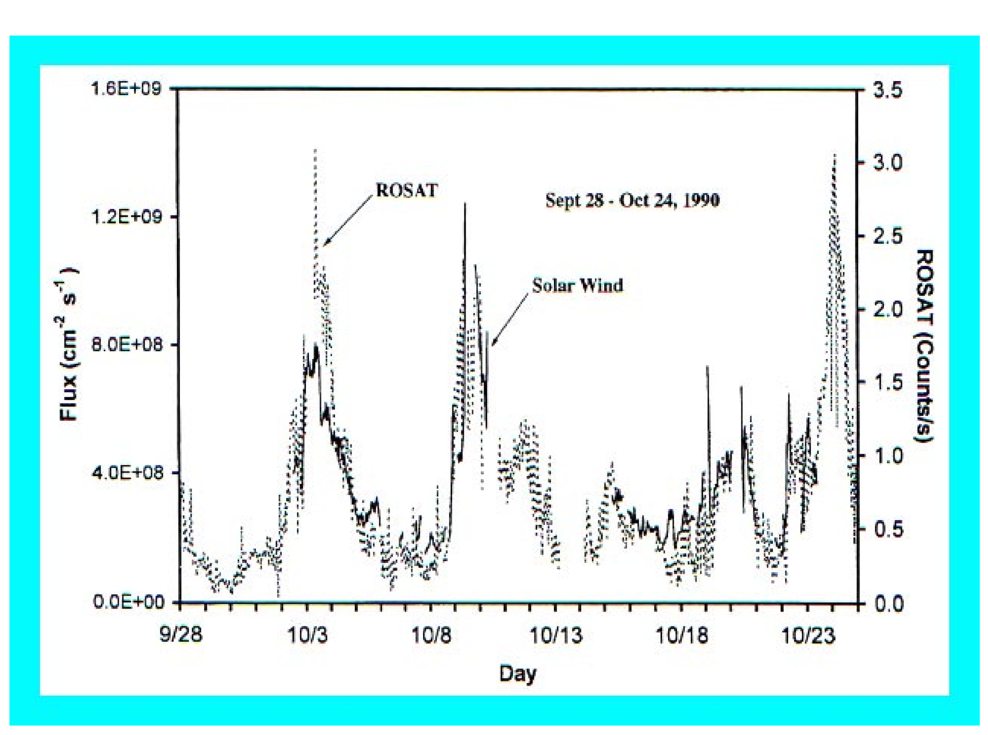

Figure 2. ROSAT Long Term Enhancement or LTE data and solar wind fluxes over the time period September 28, 1990 through October 24, 1990 from Cravens et al. [JGR, 106, 24,883, 2001].

3. ISN, Solar Wind and LTE

The work of Cravens et al. suggests that the downstream helium focusing cone should be observable in X-rays as high charge state solar wind ions charge exchange with the enhanced helium densities downstream of the Sun. Figure 3 shows the LTE data used in Cravens et al. with a running average of 23 applied from day 200 through 400 of 1990. There is clear evidence for an overall enhancement downstream. Two peaks appear to be present in the data, a peak around day 340 which corresponds to the well-known primary stream and a peak about 10 days later which may be identified with the secondary stream [Collier et al., Adv. Space Res., in press, 2003].

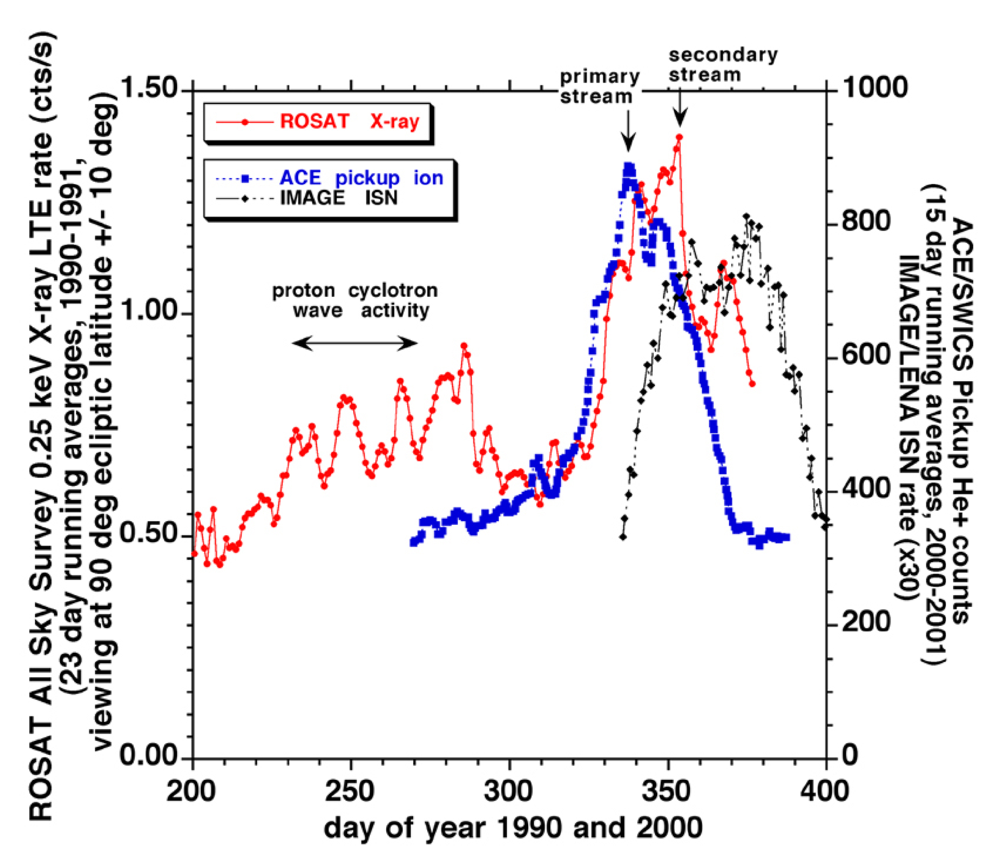

Figure 3. The LTE data used in Cravens et al.'s plot shown in Figure 2. Here a running 23 day average of the data has been used.

Because interplanetary parameters such as solar wind flux and UV can affect the amount of solar wind charge exchange that occurs, it is useful to examine these parameters at the time of the ROSAT downstream observations. Figure 4 shows the solar wind and f10.7 flux during the time of the ROSAT observations. Note that both are relatively constant over the time period of interest . So the behavior of the ROSAT data, particularly the secondary stream, does not seem to be a result of solar wind or UV changes.

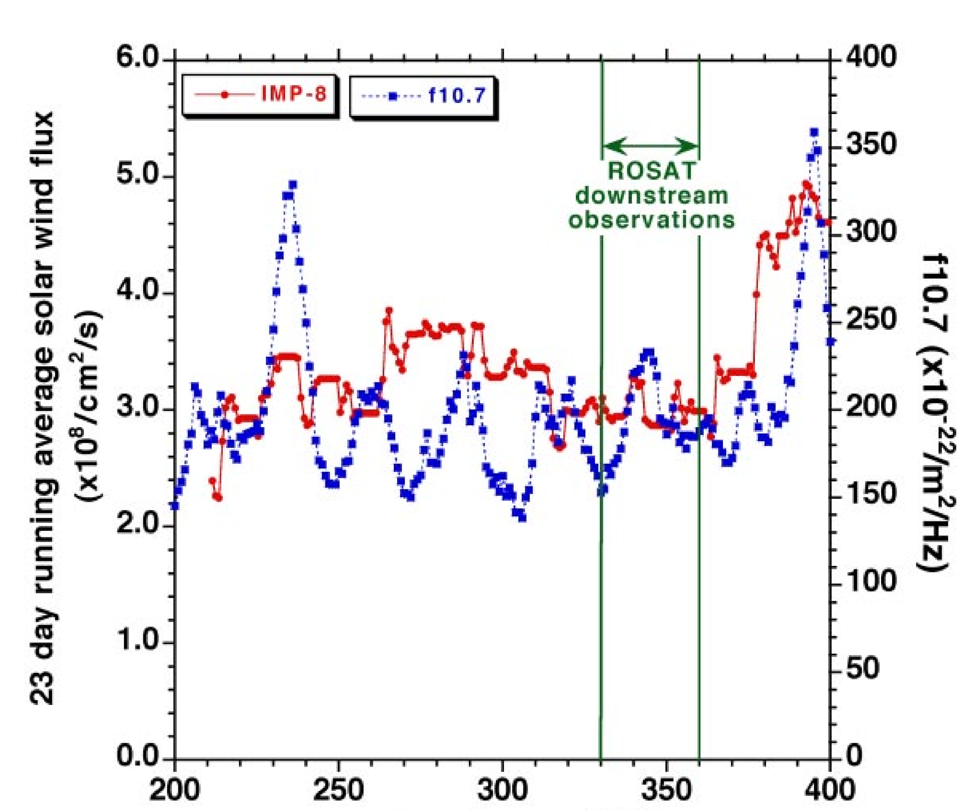

Figure 4. The f10.7 and 23 day running average solar wind flux measured by IMP 8 towards the end of 1990.

4. Primary & Secondary

There appears to be evidence for a second stream of neutral atoms entering the heliosphere at higher ecliptic longitudes than the primary stream.

It is well-established that there exists a stream of neutral atoms entering the heliosphere from a direction that places the Earth upstream of the Sun in the interstellar flow in early June of every year and downstream in early December of every year.

The data shown in Figure 3 have been taken from the LTE part of the RASS, but only when ROSAT was observing within 10 degrees of the north ecliptic pole. This is because the X-ray emission observed by ROSAT has a contribution due to the local bubble emission as well as a steady heliospheric component. By making sure that ROSAT is always looking in the same direction for these data, these two effects may be assumed constant and any changes in the emission may be attributed to changes in the ROSAT line-of-sight through nearby neutrals, namely the helium focusing cone.

The X-ray data in Figure 3 show evidence for a two peak structure. The presence of a second peak in the X-ray data may be related to a proposal made by Collier et al. [Adv. Space Res., in press, 2003] that there may be a secondary stream of neutral atoms entering the heliosphere at a higher ecliptic longitude than the primary stream by 10-40 degrees. Figure 5 shows some of the data sets that suggest the presence of this secondary stream.

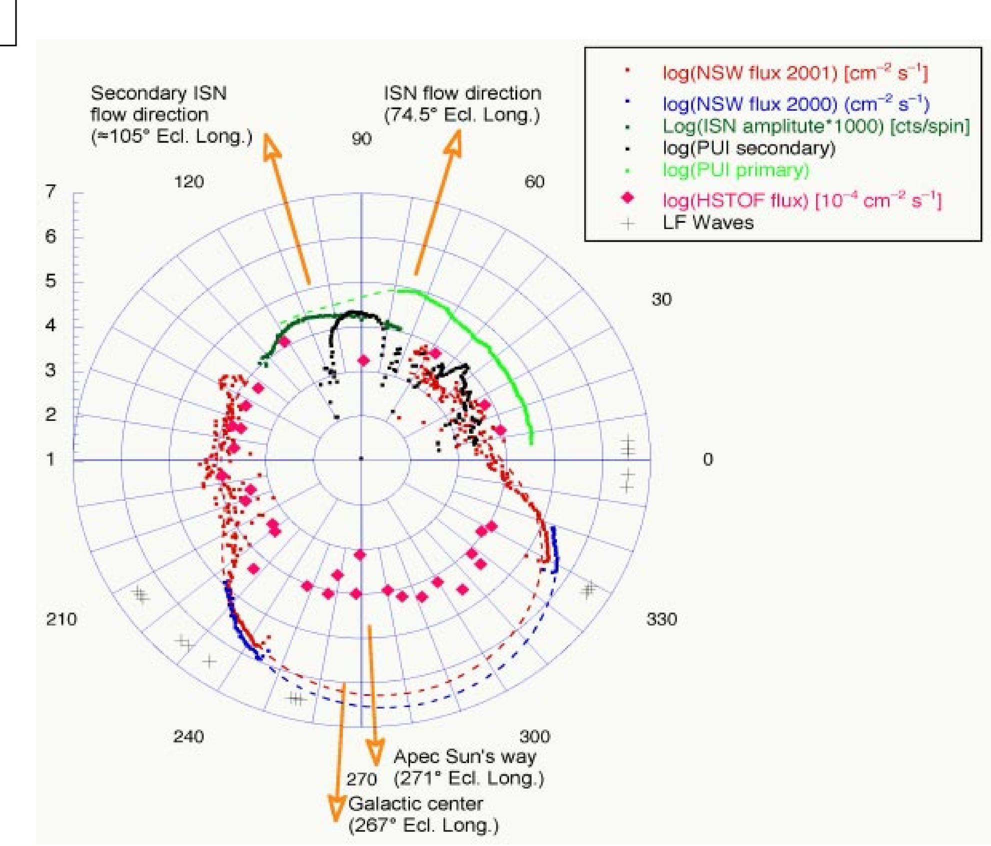

Figure 5. Figure showing five data sets related to neutral atoms which show evidence for a stream shifted from 10-40 degrees higher in ecliptic latitude than the primary stream.

5. Secondary Latitude

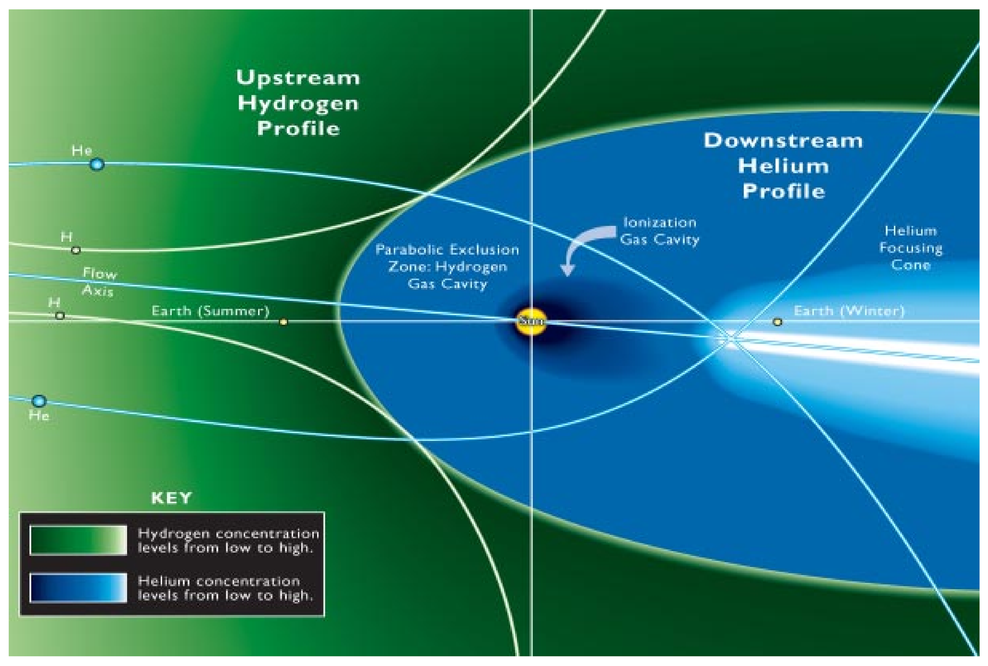

Figure 6. Interstellar hydrogen and helium profiles near 1 AU. The y-axis is aligned with the ecliptic north/south direction. The Earth is above the helium focusing cone downstream and ROSAT should observe it when looking south.

The secondary stream appears to enter the heliosphere from above the ecliptic plane, like the primary stream.

Figure 6. illustrates the qualitative distribution of interstellar hydrogen and helium near the orbit of the Earth. Hydrogen is depleted due to charge exchange with the solar wind and photoionization from the Sun, but forms a small layer of dramatically enhanced density adjacent to the parabolic exclusion zone if the ratio of radiation pressure to gravity exceeds unity.

By contrast, helium is relatively immune to charge exchange and photoionization, being depleted mostly by electron impact ionization close to the Sun. Helium, and indeed any heavy neutral, is focused downstream as illustrated by the bright downstream cone in Fig. 6.

It is well-established that the (primary) interstellar neutral stream enters the heliosphere from above the ecliptic plane, as illustrated by Fig. 6. Thus, we would expect the X-ray emission from the helium focusing cone to show an asymmetry when northward viewing is compared to southward viewing. Viewing directly ecliptic north and directly ecliptic south were natural choices since the ROSAT All-Sky Survey was effected by viewing in great circles which covered both ecliptic north and south on each scan. Always viewing the same direction assures that the effect of non-heliospheric local bubble background is a constant effect and variations with day of year can be attributed to heliospheric effects.

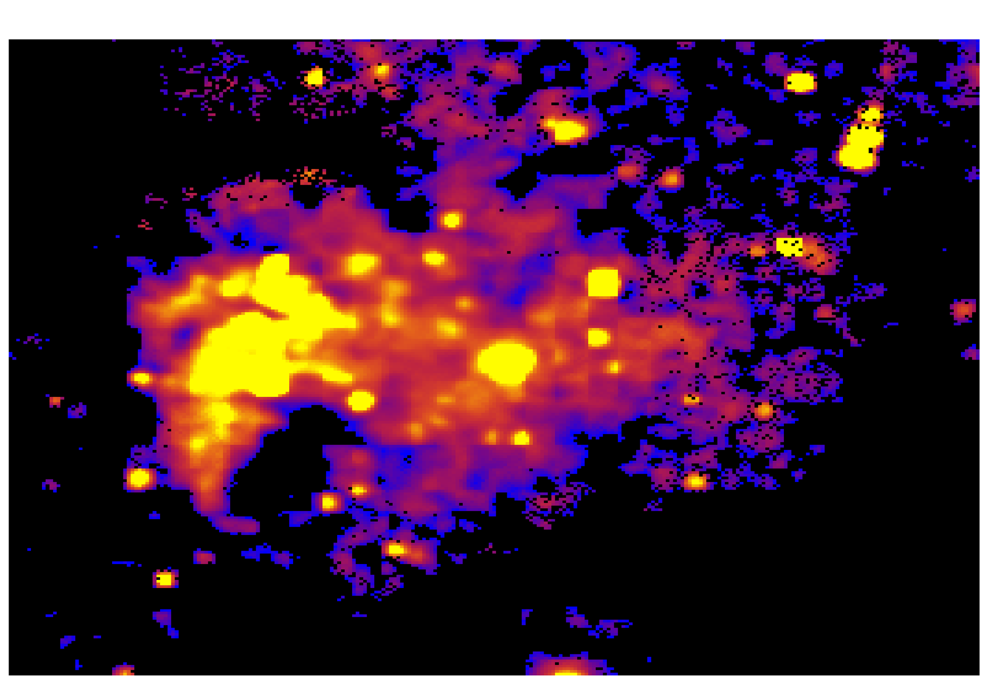

Figure 7. ROSAT image of the Large Magellanic Cloud (LMC), in ecliptic longitude 313 degrees and latitude -85 degrees. This image is 4 degrees by 4 degrees.

6. The Dust Connection?

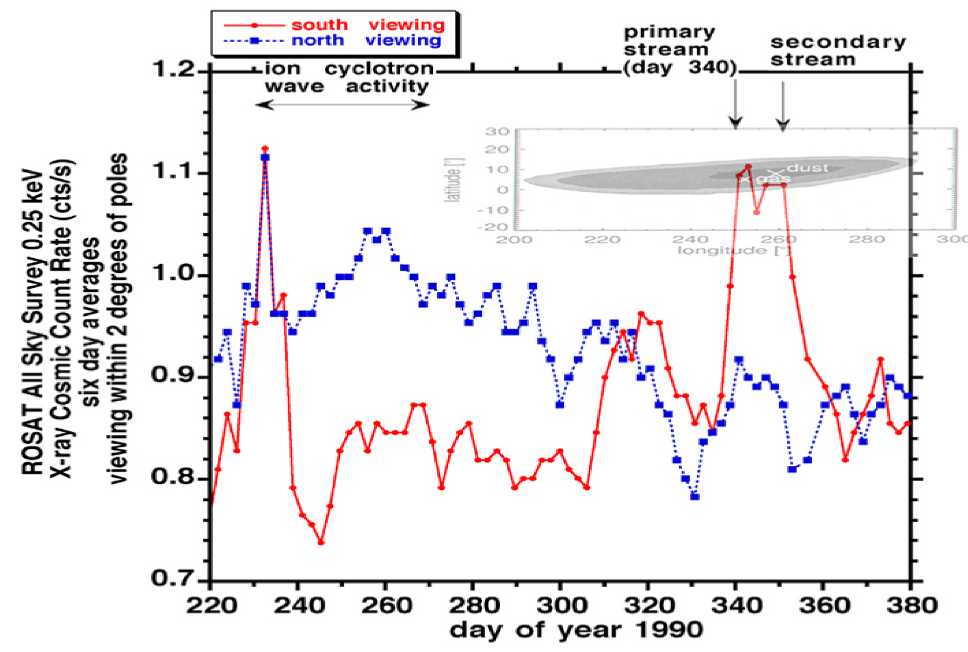

Figure 8. ROSAT X-ray rates viewing south (red) and north (blue) within two degrees of the ecliptic poles as a function of day of year. The ghost inset shows the flow direction of dust relative to the nominal upstream direction.

To avoid contamination when viewing south from the Large Magellanic Cloud, shown in Figure 7, the ROSAT data viewing north and south were restricted to only two degrees around each pole.

Figure 8 shows the ROSAT X-ray rates viewing south (red) and north (blue) as a function of day of year. Both the primary stream (peak at day 340) and the secondary stream (peak at higher ecliptic longitudes) are apparent in the data viewing south. Referring to Fig. 6 above, this suggests that both the primary and secondary streams enter from above the ecliptic plane.

There have been a few ideas suggested about the origin of the secondary stream, all of which have problems. As illustrated in the inset in Fig. 8, one idea is that the secondary stream is dust-induced, resulting from neutrals embedded in dust grains being liberated as the dust grains get close to the sun. However, the dust flux appears to be too small to explain the observations [E. Mobius, private communication]. Another idea relies on the fact that the heliosphere is very close to the edge of the local interstellar cloud in the general direction of the galactic center, as shown in Figure 9, suggesting that we may be observing the effects of charge exchange between local bubble gas and the local cloud. However, the neutrals formed would be very hot and not beam-like. Finally, as shown in Figure 10, a tilted interstellar magnetic field might introduce an asymmetry in the heliosphere, although it is not clear that the resulting neutral fluxes would be large enough to explain the observations.

The fact that the secondary interstellar neutral stream is observed in the X-ray data indicates that it is not merely a transport effect: There is a population of neutral atoms at 1 AU shifted by a substantial amount higher in ecliptic longitude than the primary stream.

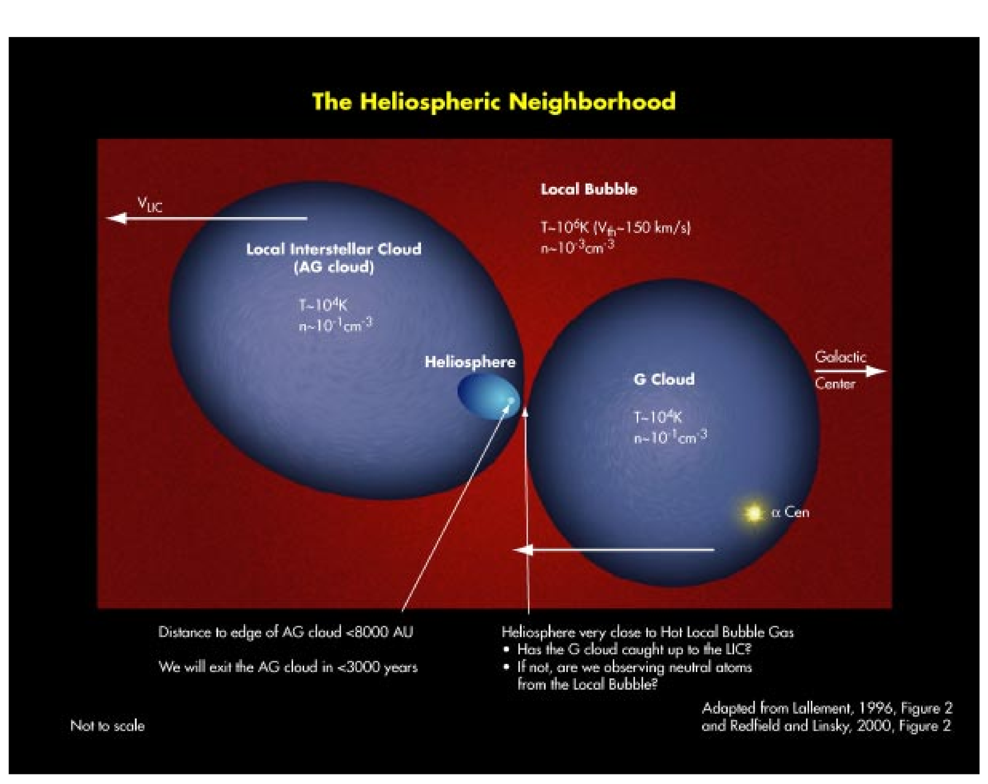

Figure 9. The heliosphere is very close to the edge of the local interstellar cloud in the approximate direction of the galactic center.

7. Craven's Alpha

The estimated value of α based on the ROSAT observations is about 7×10^{-16} eV cm^2.

Fig. 8 shows the ROSAT X-ray count rate viewing south, excluding the LTE rate. Thus, there are three contributions to this rate: a cosmic contribution from the local bubble, a steady contribution from the primary stream and a steady contribution from the secondary stream. Because the data at each day shown in Fig 8 are taken when ROSAT is observing southward or northward, the cosmic contribution is constant as a function of day of year and variations can be attributed to heliospheric effects and, in particular, steady heliospheric effects since the LTE rate is not included here.

There are two major assumptions that go into estimating a value for α. First, that the downstream enhancement is due primarily to an increase in the local helium density near the spacecraft (i.e. that the increase is due to the focusing cone). Second, that the secondary stream is not directly related to the primary stream. This is because we are subtracting off the secondary stream in this analysis. In Cravens [GRL, 24, 105, 1997], he derived the following expression for the X-ray power produced per unit time where α is a constant representing the detailed atomic physics, n_n is the neutral density, n_{sw} is the solar wind density and u_{sw} is the solar wind speed:

$$P_{\mathrm{X-ray}} = \alpha\, n_n\, n_{sw}\, u_{sw} \ \ \mathrm{eV\ cm^{-3}\ s}$$

The X-ray intensity at Earth, I, in a given direction can be determined by integrating the above equation over pathlength:

$$4\pi I = \int P_{X-ray}\,dr = \alpha\, n_{\mathrm{sw}}\, u_{\mathrm{sw}} \int n_{\mathrm{n}}\,dr$$

Since α is a parameter that is not known very accurately, we can solve for α in terms of the observed intensity increase, I, the column density, Γ, and the solar wind flux, Φ:

$$\alpha = \frac{4\pi\ I}{\Phi\ \Gamma}$$

Evaluating this expression requires some focusing cone modeling, such as that shown in Figure 11 which can be used to try to separate the heliospheric from non-heliospheric contributions to the X-ray emission, as shown in Figure 12, and estimate α:

$$\alpha = \frac{4\pi \cdot 8\mathrm{x}10^{3}}{3\mathrm{x}10^{8} \cdot 4.5\mathrm{x}10^{11}} = 7\mathrm{x}10^{-16}\ \mathrm{eV\ cm}^2$$

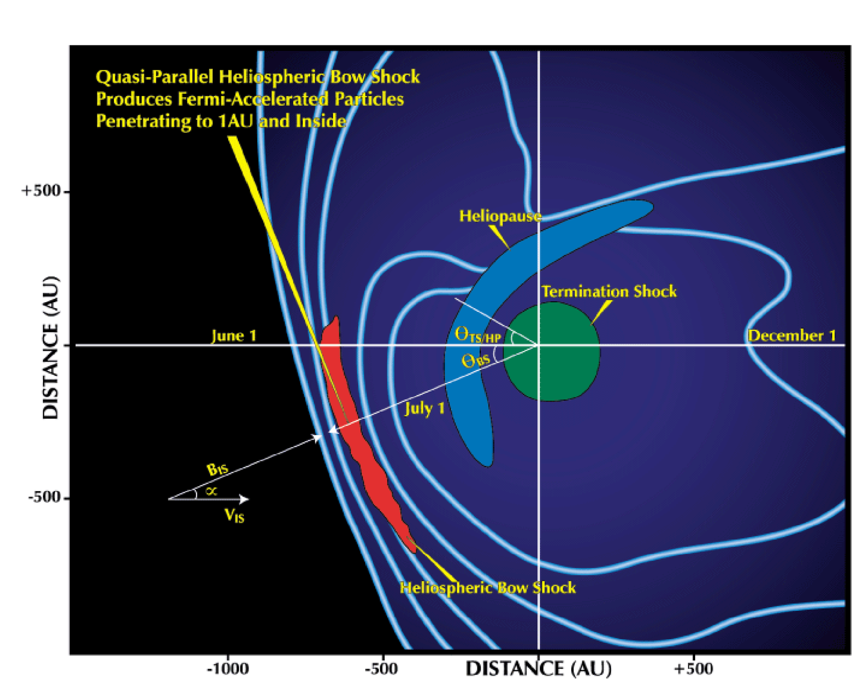

Figure 10. The presence of an interstellar magnetic field may cause an asymmetry in the configuration of the heliosphere.

8. Conclusion

X-ray observations of solar wind charge exchange have proven a useful technique for inferring the distribution of interstellar neutrals in the vicinity of the Earth.

Since X-rays probe directly the distribution of neutral atoms, one does not need to be concerned about potential transport or other effects. Furthermore, it is a remote sensing technique that is not limited to in-situ observations.

The analysis presented here, although preliminary and still subject to more detailed modeling work, appears to be consistent with a value of α of about 7×10^{-16} eV cm^2, a heliospheric contribution to the diffuse X-ray flux ranging from 18-40% of the total, and the presence of a broad secondary stream which, based on fits to the X-ray rates, may have 3-4 times the neutral density of the primary stream at 1 AU.

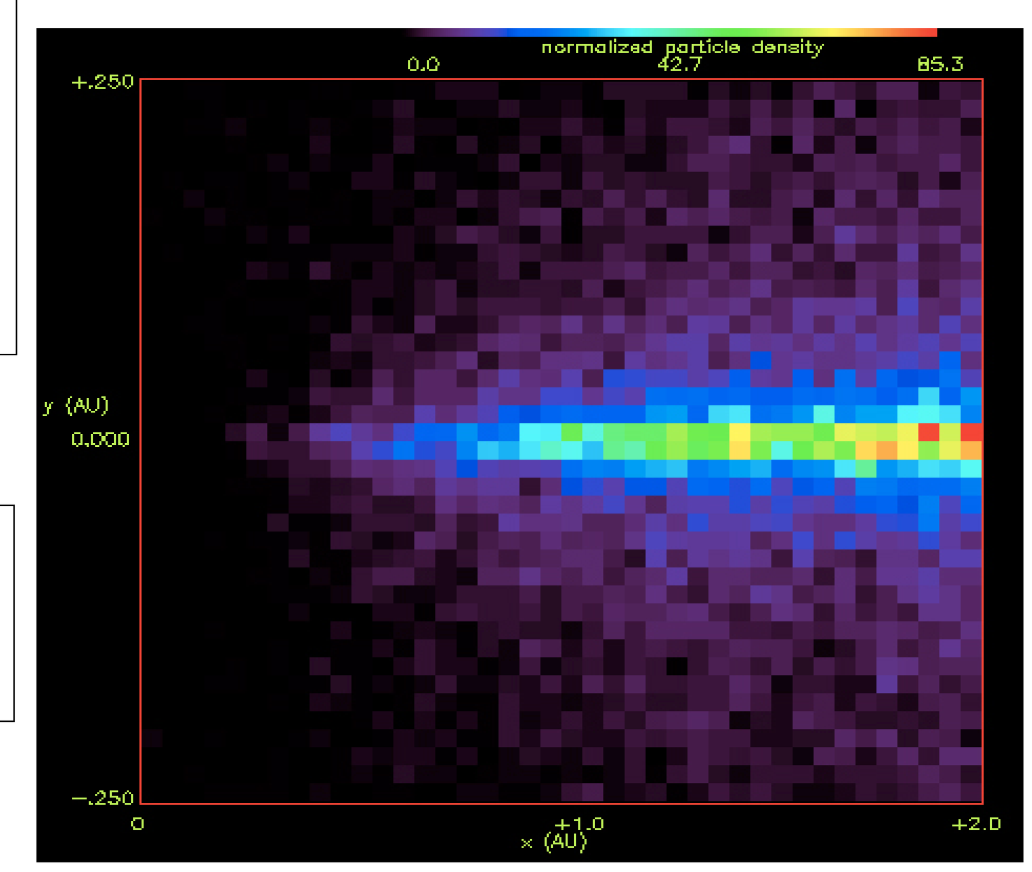

Figure 11. A helium focusing cone simulation.

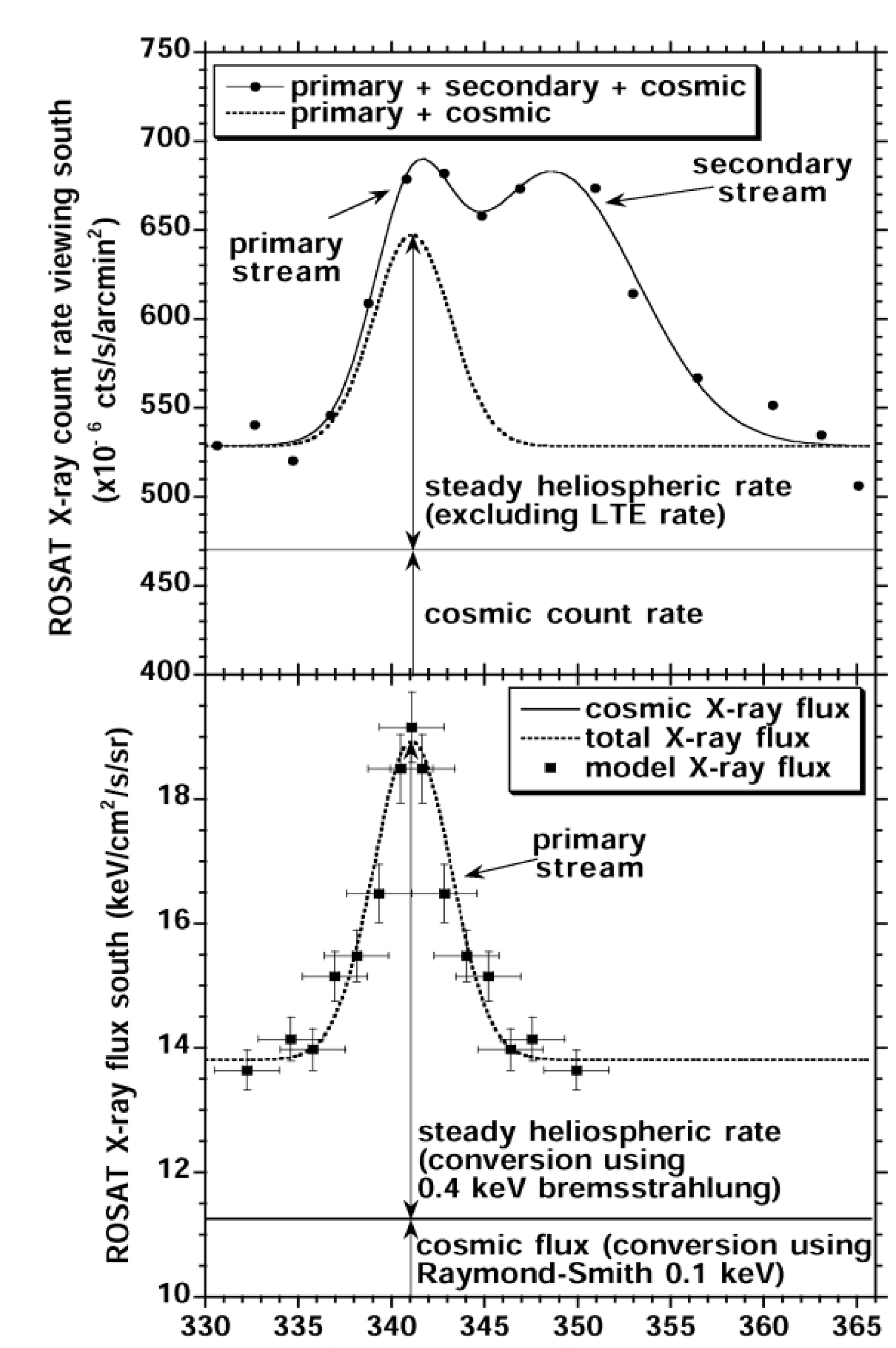

Figure 12. ROSAT X-ray count rates and fluxes attributed to heliospheric and local bubble contributions.